Papers

Relationships between inherent optical properties in the Baltic Sea for application to the underwater imaging problem*

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Abstract

Statistical relationships between coefficients of light attenuation, scattering and backscattering at wavelength 550 nm derived from series of optical measurements

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performed in Baltic Sea waters are presented. The relationships were derived primarily to support data analysis from underwater imaging systems. Comparison of these relations with analogous empirical data from the Atlantic and Pacific Oceans shows that the two sets of relationships are similar, despite the different water types and the various experimental procedures and instrumentation applied. The apparently universal character of the relationships enables an approximate calculation of other optical properties and subsequently of the contrast, signal/noise ratio, visibility range and spatial resolution of underwater imaging systems based on attenuation coefficients at wavelength 550 nm only.

1. Introduction

Satellite, airborne and shipboard imaging, and lidar systems are valuable tools for investigating the World Ocean. They are used in underwater manned, remote-controlled and robotic vehicles in the search for minerals and sunken objects on the sea floor. In some applications, imaging systems are used to draw maps of distributions of vegetation and bottom sediments. In ecological and environmental studies imaging systems serve as a tool for detecting water pollution and bottom debris, for monitoring fish spawning regions, changes to the sea bed, beach destruction, the amount and type of suspended matter transported in river and current flows, and a multitude of other effects of man-made and natural processes (Dolin & Levin 1991, Fournier et al. 1993, Tang et al. 1998, Stemmann et al. 2000, Mayer et al. 2002, Dolin et al. 2006).

Modern theories of underwater imaging (Dolin & Levin 1991, 2004, Zege et al. 1991) and of imaging through a wave-roughened sea surface (Dolin et al. 2006), focusing as they do on optimizing imaging systems, show that the most important parameters determining visibility in the water (contrast, signal/noise ratio (SNR), visibility range and spatial resolution) depend on the inherent optical properties of water (IOP) to a greater extent than on the parameters of the imaging system itself and can be found if the coefficients of light scattering b, backscattering b_b and absorption a (or attenuation $c = a + b$) are known. All these IOPs depend strongly on wavelength λ. However, all imaging systems, including many of the laser-based systems, work in the spectral region close to 550 nm. As shown by Levin & Radomyslskaya (2007), the wavelength corresponding to the maximum water transparency and maximum visibility range when observations are made through a narrow spectral filter varies monotonically from 500 nm for the clearest ocean water to 590 nm for the most turbid coastal water, whereas the maximum visibility range, when observed by a receiver with a spectral sensitivity close to that of the human eye, is located for all waters in the spectral region of 530–550 nm with an accuracy of several per cent (see also Zaneveld & Pagau

2003). Consequently, in order to solve any problem of underwater imaging, we only need to know the water's IOPs in the spectral range close to 550 nm.

The standard optical instruments on most research vessels are light attenuation meters (see e.g. Levin et al. 2003); hence, the light attenuation coefficient c is the water's most frequently studied optical parameter and measurements of c are often the only source of information about the optical properties of a water body. Therefore, it would be of value to be able to reliably estimate the coefficients of light scattering or absorption (b or a) and of backscattering b_b from only the light attenuation coefficient c. Besides, it was shown (Levin & Radomyslskaya 2007) that the value of c(555 nm) is uniquely associated with the Secchi depth. Thus the relations between c, b and b_b make it possible to estimate parameters of underwater imaging systems using only the charts of geographical distribution of the Secchi depth.

It is known (Prokudina & Pelevin 1972, Kopelevich 1983) that the variability of seawater absorption a close to wavelength $\lambda = 550$ nm is relatively small, and that the variations in the attenuation coefficient c are determined mainly by variations in the scattering coefficient b. Thus, one should expect a high correlation between c and b in this spectral region.

The aim of this paper is to establish relationships between c and b for Baltic Sea waters and to explore the possibility of estimating the scattering coefficient b and backscattering coefficient b_b at wavelengths close to $\lambda = 550$ nm by using the light attenuation coefficient c in the same spectral region only. Such relationships, if statistically robust and of general applicability, can later be applied to address underwater imaging problems.

2. In situ data and methods

Optical and accompanying data were collected during 14 cruises performed in the southern Baltic in 1999–2005 on board the research vessel 'Oceania' (Figure 1).

In situ measurements of light absorption and attenuation coefficients of suspended and dissolved matter, $a_m(\lambda) = a(\lambda) - a_w(\lambda)$, $c_m(\lambda) = c(\lambda) - c_w(\lambda)$, where $a_w(\lambda)$ and $c_w(\lambda)$ are the absorption and attenuation coefficients of pure seawater, were performed with an ac-9 spectrophotometer (WetLabs USA) at wavelengths λ of 412, 440, 488, 510, 532, 555, 650, 676 and 715 nm. The instrument was calibrated in pure water and routinely checked for stability by air readings. A temperature and salinity correction was applied according to the instrument's manual. The ac-9 system employs the measurement technique of light absorption with a reflecting tube

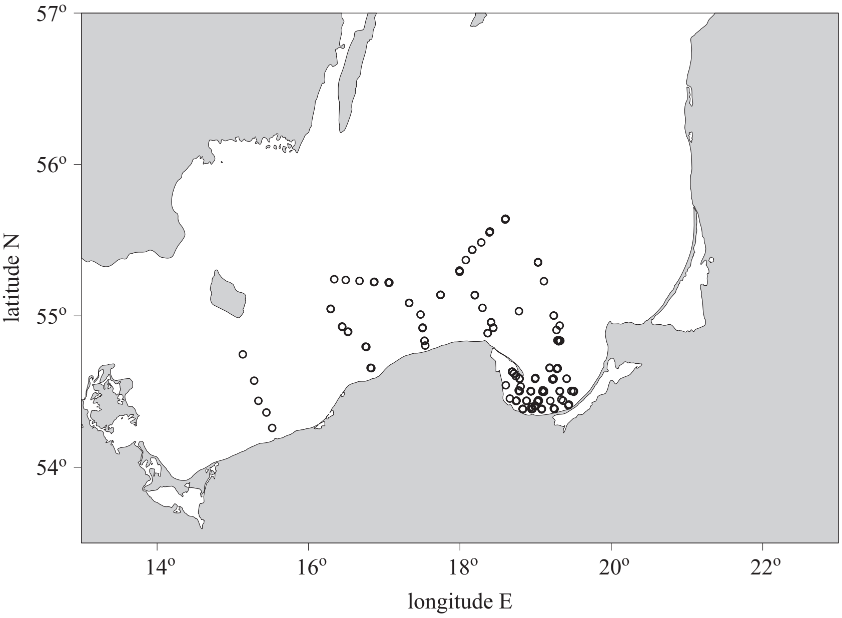

Figure 1. Location of the sampling stations in the Baltic Sea, 1999–2005

(Kirk 1992). This requires a further scattering correction to be applied to the absorption channels. The correction that was applied is referred to as 'proportional' (Zaneveld et al. 1994), which assumes a zero light absorption coefficient at the reference wavelength $\lambda_{\text{ref}} = 715$ nm. The absorption and attenuation coefficients are measured with an estimated error of 2.5%–5%.

The vertical profiles of light absorption $a_m(\lambda)$ and attenuation $c_m(\lambda)$ were sampled with an average depth resolution of 25 to 30 cm. Profiles of $a_m(\lambda)$ and $c_m(\lambda)$ were median-smoothed and interpolated (nearest neighbour method) to full depths $(0, 1 \ldots \text{m})$. After the required corrections were applied to $a_m(\lambda)$ and $c_m(\lambda)$, light scattering coefficients $b_m(\lambda)$ were calculated from $c_m(\lambda) - a_m(\lambda)$.

To prevent any influence on the statistics of extreme values of c and b (likely to be found in the vicinity of river mouths, coastal areas or the near-bottom layer), the data used were limited to the range of 'non-outlying' values for the median statistic calculated for the entire data set. The resulting data set was split into summer (April–October) and winter (November–March) seasonal sub-sets. The summer data set consists of 162 vertical profiles (10 045 elements) with depth range $z = 0$–125 m, and range of values $c_m(555 \text{ nm}) = 0.070$–$1.910 \text{ m}^{-1}$ and $a_m(555 \text{ nm}) = 0.010$–$0.250 \text{ m}^{-1}$. The winter data set contains 53 vertical profiles with 3297 elements, with depth range $z = 0$–91 m, and range of values $c_m(555 \text{ nm}) = 0.080$–$1.580 \text{ m}^{-1}$ and $a_m(555 \text{ nm}) = 0.018$–$0.180 \text{ m}^{-1}$.

3. Environmental background

The inherent optical properties of Baltic waters have been investigated for a long time (Lundgren 1976, Dera 1992, Sagan 2008). Its spectral properties, already quite well known, are governed mostly by the large quantities of dissolved organic material (CDOM) (Kowalczuk 1999, Kowalczuk et al. 2010) and the relatively high concentrations of both organic and inorganic suspended particulate matter (SPM), especially in the upper 30 m layer during the summer (Sagan 2008). These factors are well reflected by the mean light attenuation spectra for Baltic waters (Figure 2). The elevated attenuation at 400–500 nm results from light absorption by CDOM in that spectral range. The absorption maxima due to phytoplankton pigments are masked here by CDOM absorption (shortwave range) and by absorption by water molecules (long-wave range). The higher light attenuation in the whole spectral domain at depths from 0 m to 30 m, compared to attenuation at depths below 30 m, is due mainly to the presence of SPM in the surface water layer.

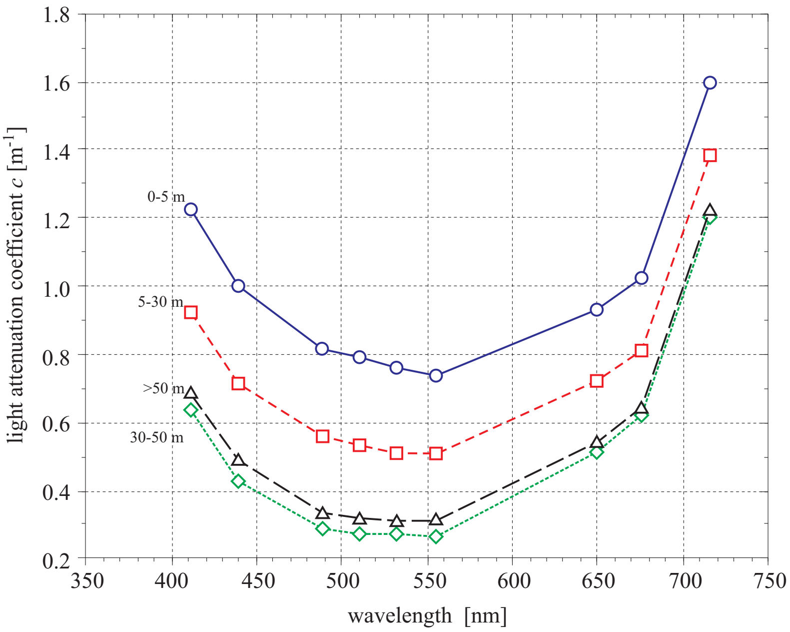

Figure 2. Typical spectra of light attenuation in selected depth ranges in the Baltic, light absorption by pure water included (Sagan 2008)

These spectral features, specific to Baltic waters, result in a maximum water transparency for light of wavelength 520–550 nm, which is the spectral range within which underwater imagery systems operate. This is also the spectral range within which the human eye is the most sensitive.

There are two distinct seasonal hydrological regimes observed in the Baltic (Eilola 1997), referred to as 'summer' and 'winter' in their developed stages. Typically between April and October the upper water layer is well mixed down to 30 m, with water temperatures reaching 20°C. This water layer is separated from the water mass below by a strong thermocline. Under the winter regime (November–March), the water column is uniform in respect of temperature and salinity down to the depth of the permanent halocline, which is usually 55 m to 60 m (Voipio (ed.) 1981). The changes in the inherent water optical properties of the water column follow this pattern (Sagan 2008). In effect, during the summer months the 0–30 m water layer is characterized by relatively high light attenuation coefficients, $c(555\ \text{nm}) = 0.44\text{–}0.67\ \text{m}^{-1}$, while typical attenuation coefficients for the waters below at that wavelength are 0.20–0.24 m^{-1}. The latter values are also typical of the entire water column over the depth range 0–50 m under the winter regime. Mean light attenuation coefficients at 555 nm in the waters below 60 m during both seasons range from 0.24 to 0.38 m^{-1}, with a slight increase during winter months (Sagan 2008).

4. Relations between the attenuation and scattering coefficients for wavelength 555 nm in the Baltic Sea

Relations between $b_m(555\ \text{nm})$ and $c_m(555\ \text{nm})$ for Baltic waters are presented in Figure 3. The data sets for the summer and winter periods were additionally divided into depth ranges of 0–30 m and > 30 m. This data split follows the aforementioned known seasonal vertical differentiation of optical properties caused by hydrological stratification.

The respective regression lines (for the clarity we omit constant light wavelength in the equations) plotted on the basis of the measurement data by the least squares method in Figures 3a,b,c,d are:

$$b_m = 0.9308(\pm 0.0009)c_m - 0.0363(\pm 0.0004), \tag{1a}$$

$$b_m = 0.9846(\pm 0.0002)c_m - 0.0507(\pm 0.0005), \tag{1b}$$

$$b_m = 0.9315(\pm 0.0011)c_m - 0.0367(\pm 0.0002), \tag{1c}$$

$$b_m = 0.9381(\pm 0.0019)c_m - 0.0376(\pm 0.006). \tag{1d}$$

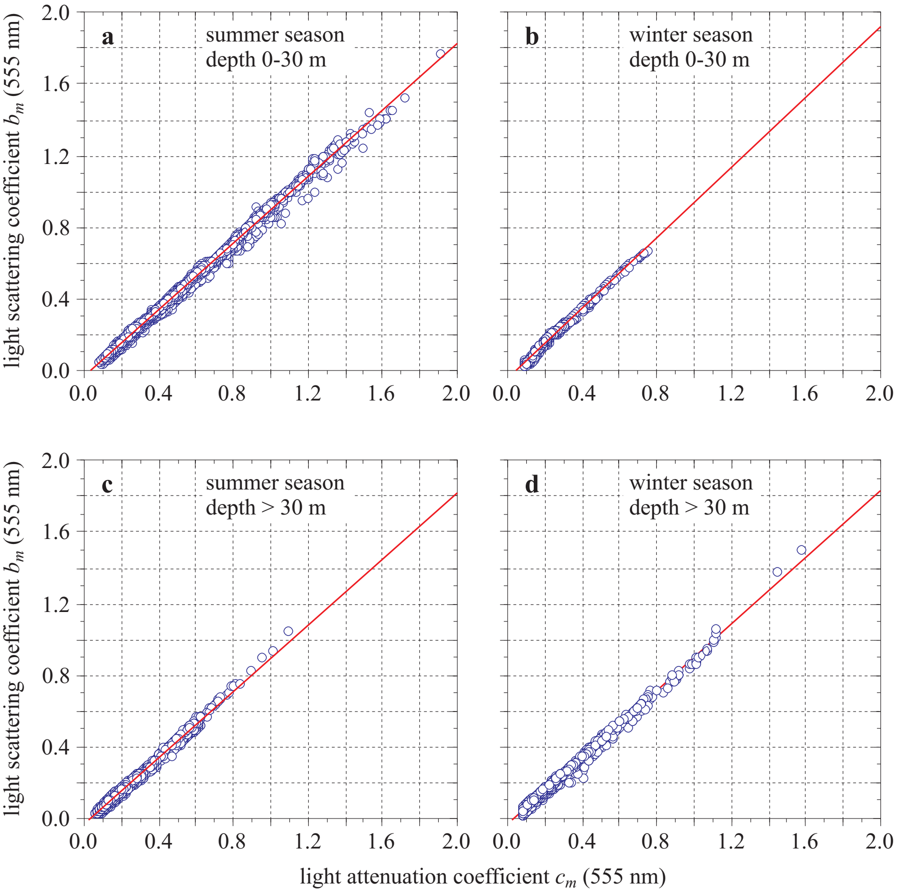

Figure 3. The data (open circles) and regression lines of the measurements of the light attenuation coefficient c_m and the light scattering coefficient $b_m = c_m - a_m$ for summer (a, c) and winter (b, d) regimes at depths $z \leq 30$ m (a, b) and $z > 30$ m (c, d). The coefficient of determination $r^2 > 0.999$ for all four groups

There is no statistical difference between b_m(555 nm) and c_m(555 nm) relations for the summer and winter < 30 m data sets (Figures 3a, 3c and 3d). However, all the relations differ statistically from the relation for the winter 0–30 m data set (Figure 3b, equation (1b)).

Following these results, the subsequent analyses were performed for data aggregated for the whole water column under the winter and summer regimes, and for all the data together.

The regressions for the aggregated data obtained by the least squares method are:

$$b_m = 0.9563 c_m - 0.0431, \tag{2a}$$

$$b_m = 0.9337 c_m - 0.0370, \tag{2b}$$

$$b_m = 0.9380 c_m - 0.0385, \tag{2c}$$

where equation (2a) relates to the winter measurements, equation (2b) to the summer measurements, and equation (2c) is the relation for the pooled winter and summer data sets.

The root mean squared error (RMSE) for the experimental data from equations (2a,b,c) are equal to 1.44×10^{-2} m^{-1}, 1.37×10^{-2} m^{-1} and 1.41×10^{-2} m^{-1}, $r^2 = 0.9948$, 0.9965 and 0.9961 respectively. As can be seen, the correlation between b_m and c_m in the Baltic Sea is very strong and fairly stable in respect of season and water depth.

When marine biological and ecological problems are analysed, it is standard practice and convenient to use the optical properties of dissolved and suspended matter, without taking account of the optical properties of pure water, that is, b_m, c_m and a_m. Nevertheless, when we are dealing with imaging or underwater visibility issues, a knowledge of the total optical properties is required, that is

$$b = b_m + b_w, \qquad c = c_m + c_w, \qquad a = a_m + a_w, \tag{3}$$

where b_w, c_w and a_w are the coefficients of scattering, attenuation and absorption of pure sea water respectively. According to Pope & Fry (1997) and Smith & Baker (1981), $a_w(555 \text{ nm}) = 0.0596$ m^{-1}, $b_w(555 \text{ nm}) = 0.0019$ m^{-1}; hence $c_w(555 \text{ nm}) = 0.0615$ m^{-1}.

Using equation (3) and the values of $b_w(555$ nm) and $c_w(555$ nm), one can obtain from equations (2a,b,c) the corresponding correlations for the total optical properties b and c for winter (4a), summer (4b) and both winter and summer (4c):

$$b = 0.9563c - 0.1000, \tag{4a}$$

$$b = 0.9337c - 0.0925, \tag{4b}$$

$$b = 0.9380c - 0.0942. \tag{4c}$$

Since the optical parameters of pure sea water are constant, the RMSE in equations (4a,b,c) remain the same as for equations (2a,b,c).

To find out whether the relations obtained for Baltic Sea waters are local or have a general character, we compared the relation between b and c found for Baltic waters with the results of similar research performed in other regions of the World Ocean.

On the basis of some 70 measurements in the Atlantic and Pacific Oceans and in the Arabian Sea, Levin & Kopelevich (2007) found that in ocean water the range of c at wavelengths close to $\lambda = 550$ nm was between 0.08 and 2.5 m^{-1} and that the single scattering albedo for 550 nm $\omega_0 = b/c$ varied from 0.3 to 0.9. The ocean measurements were taken by Kopelevich during a cruise of the 'Dmitry Mendeleev' from Kaliningrad to Vladivostok via Panama, Honolulu and Suva, embracing the Gulf Stream, Caribbean Sea, Gulf of Panama, Cromwell Stream, Tonga Hollow, Northern and Southern trade-wind Streams and Galapagos Islands (Kopelevich et al. 1974). Measurements in the Arabian Sea were collected by the National Institute of Oceanography (Goa, India) and were presented and discussed by Levin et al. (2001). The linear relation between b and c calculated for those data yields

$$b = 0.944c - 0.048 \tag{5}$$

with the RMSE = 0.033 m^{-1}.

The relations (equation (4)) based on the measurements in the Baltic Sea turn out to be stronger (i.e. a lower RMSE) than equation (5) for ocean waters given by Levin & Kopelevich (2007). However, it should be noted that the relations compared were obtained in different sea regions and also with different instruments. The attenuation and scattering of Levin & Kopelevich were also measured separately using an SGN instrument (attenuation) and a small-angle scattering meter (scattering coefficient) (Kopelevich et al. 1974).

Figure 4 shows the data measured in the Baltic Sea (open circles); the line corresponds to ocean water (equation (5)).

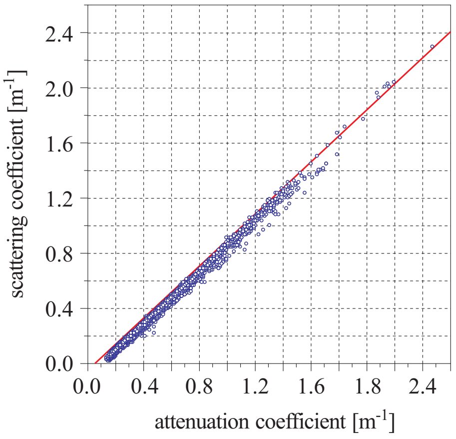

Figure 4. Relations between the scattering coefficient and the attenuation coefficient at 555 nm. The open circles show the data sampled in the Baltic Sea at 555 nm, and the line represents equation (5) obtained for ocean waters at 550 nm by Levin & Kopelevich (2007)

The RMSE of estimation for ocean waters (Figure 4) is 0.033 m^{-1} and the coefficient of determination $r^2 = 0.9899$, while for data from the Baltic Sea the corresponding values are 0.0141 m^{-1} and $r^2 = 0.9961$.

It can be seen that despite the different sea regions and the different experimental procedure and instrumentation used, the relations resemble each other very closely. Consequently, it can be concluded that the strong linear dependency between b and c at this wavelength is not restricted to Baltic waters only. A similarly strong linear relationship has been described by several authors (see, for example, Lundgren 1976, Voss 1992 or Barnard et al. 1998). They show that the linear nature of this kind relationship is maintained in the waters of various seas and oceans. In particular, the comparison by Levin & Kopelevich (2007) of equation (5) with data of b and c measured by Morel & Prieur (1977) and Shoonmaker et al. (1994) in coastal and ocean waters shows good agreement between equation (5) and these data. We may therefore expect that the relations between other optical parameters based upon the Baltic Sea IOP data set and examined in the following section will also hold for other seas.

5. Relation between the backscattering and attenuation coefficients for wavelength 555 nm in the Baltic Sea

The backscattering coefficient b_b and backscattering probability $\tilde{b}_b = b_b/b$ are the key parameters for imaging and as well as for remote sensing inversion algorithms (Roesler & Boss 2003).

On the basis of the established linear relation between c and b for Case 1 and Case 2 water areas, Levin & Kopelevich (2007) obtained relationships between the single scattering albedo and the backscattering probability $\tilde{b}_b = b_b/b$ for wavelengths close to 550 nm:

$$\tilde{b}_b = 0.01796/\omega_0 - 3.7 \times 10^{-5} \approx 0.018/\omega_0, \tag{6a}$$

$$\tilde{b}_b = 0.0183/\omega_0 - 0.0094. \tag{6b}$$

Equation (6a) refers to Case 2 waters, equation (6b) to Case 1, oceanic waters.

To estimate $\tilde{b}_b$ and the similar relationship for the Baltic Sea, let us write

$$b_b = b\ \tilde{b}_b = b_{bm} + b_{bw} = b_m\ \tilde{b}_{bm} + b_w\ \tilde{b}_{bw}, \tag{7}$$

where b_{bm} and $\tilde{b}_{bm}$ are the backscattering coefficient and backscattering probability of suspended matter, and b_{bw} and $\tilde{b}_{bw} = 0.5$ are the backscattering coefficient and light backscattering probability of pure sea water. It follows from equations (2), (7) and the value $b_w(555 \text{ nm}) = 0.0019 \text{ m}^{-1}$ that for the Baltic Sea

$$b_b = [0.9380(c - c_w) - 0.0385]\,\tilde{b}_{bm} + 0.00095. \tag{8}$$

Thus, the relation between the backscattering coefficient b_b and the attenuation coefficient c depends on the backscattering probability $\tilde{b}_{bm}$.

The value of $\tilde{b}_{bm}$ frequently used in the literature is $\tilde{b}_{bm} = 0.019$, as obtained by Petzold for a wavelength of 514 nm (Petzold 1972) or is close to it, e.g. $\tilde{b}_{bm} = 0.018$–0.020 (Kirk 1984, Morel 1988, Gordon 1989, Mobley et al. 1993, Sathyendranath & Platt 1997, Lee et al. 1999). More recent research on backscattering probability in the Oslo Fjord (Aas et al. 2005) reports mean values of $\tilde{b}_b$ for 555 nm close to 0.021, with a standard deviation of 0.013. Estimates published by Whitmire et al. (2007), which are based on data from coastal and open ocean waters, yield mean values of $\tilde{b}_b$ for 555 nm in the range 0.011–0.016, which are slightly lower than Petzold's values. In contrast to this, the account of spectral variability of $\tilde{b}_b$ given by McKee et al. (2009) results in $\tilde{b}_b = 0.05$ for 550 nm, which is a significantly higher value. However, the latter research was performed in a confined area of mineral-rich waters. In all instances the authors account for significant (up to 30%) uncertainties in their estimates, which are the result of the propagation of instrumental errors, uncertainties related to methodological assumptions and the natural variability of the properties measured.

In view of the above, for Case 2 waters, in which the concentration of mineral SPM significantly exceeds the concentration of particles of biological origin, that is $b_x \gg b_c$ (b_x and b_c are the respective scattering coefficients of sediment and chlorophyll, $b_m = b_x + b_c$), Petzold's value of $\tilde{b}_m(555 \text{ nm}) = 0.019$ seems to be acceptable for our estimates.

Substituting the value of $\tilde{b}_m(555 \text{ nm}) = 0.019$ and $c_w(555 \text{ nm}) = 0.0615 \text{ m}^{-1}$ in equation (8), we obtain:

$$b_b = (0.01782c - 8.77 \times 10^{-4}), \tag{9}$$

and for the backscattering probability using equations (4c) and (7):

$$\tilde{b}_b = (0.01782c - 8.77 \times 10^{-4})/(0.9380c - 0.0942). \tag{10}$$

The relations described by equations (10) for Baltic water and (6a) for Case 2 waters are shown in Figure 5.

The relations between the backscattering probability and the attenuation coefficient for the Baltic Sea and for other Case 2 waters differ for $c(555 \text{ nm}) > 0.6 \text{ m}^{-1}$, but the difference is less than 2% (note that the Y axis does not start from zero). For light attenuation coefficients $< 0.3 \text{ m}^{-1}$

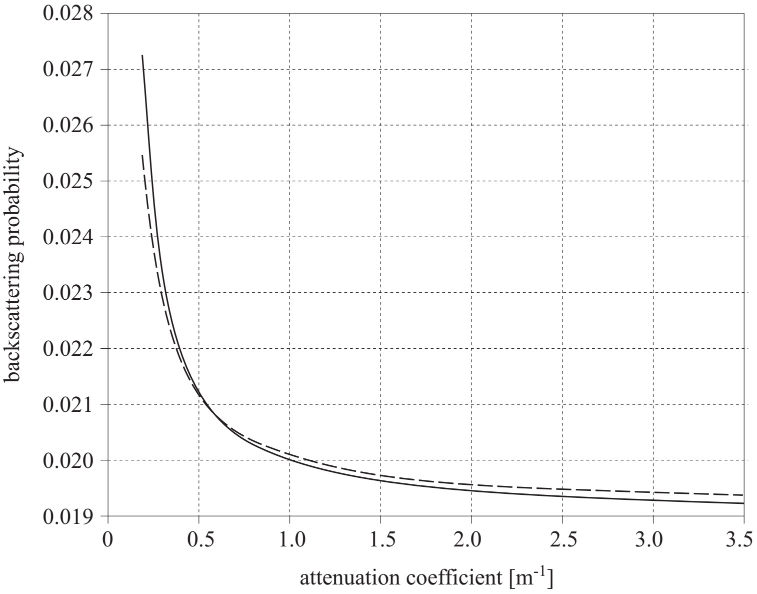

Figure 5. Relation between the backscattering probability and the attenuation coefficient for 555 nm, the Baltic Sea (solid line) and for Case 2 waters for 550 nm (dashed line)

the differences rise to 6% at c(555 nm) = 0.2 m^{-1}, i.e. for the lowest values of c(555 nm) registered in Baltic waters in the data set analysed.

6. Conclusions

The relationships found between light attenuation, scattering and backscattering coefficients in the spectral range close to 550 nm enable a range of inherent optical properties of Baltic waters to be determined. Despite the different experimental procedures and instruments used, the relations between attenuation, scattering and backscattering coefficients derived for the Atlantic and Pacific Oceans and the Arabian Sea agree very well with the results obtained for the Baltic Sea. They are also consistent with reports of similar dependencies between IOP parameters for other seas. This leads to the conclusion that established relations between b, $\tilde{b}_b$ and c for the spectral range close to 550 nm are not limited to Baltic waters, but are of a universal nature. Of course, this does not mean that these relations hold for all type of waters. In particular, they may fail in hyperproductive waters with high concentrations of chlorophyll and in very pure waters with $c(550 \text{ nm}) < 0.1$ m^{-1}, since the IOP data underlying the relationship did not cover the conditions of such waters. However, the universal relationship may be used to estimate the efficiency of applying imaging systems in a sea region where IOP, apart from c or Secchi depth, are unknown.

Knowledge of just the light attenuation coefficient enables the most important parameters of underwater imaging systems – contrast, signal/noise ratio, visibility range and spatial resolution – to be computed. With these parameters the optimal mode of building an imaging system designed for a specific application can then be calculated.

The further study of the nature of the relations between basic IOP parameters and the verification of their apparent universal character may be of special importance, especially following the advent of autonomous observation platforms such as gliders. These are typically equipped with a payload of robust but simple, low-maintenance, light attenuation or scattering sensors (Johnson et al. 2009). The existing close relations between basic IOPs open up the possibility of estimating a range of other optical parameters, which would otherwise require much more advanced instrumentation.

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